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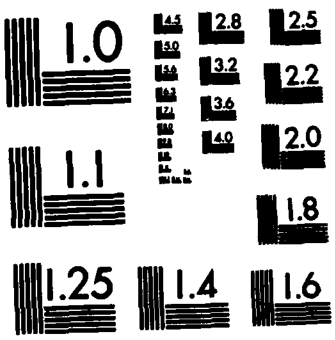

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REVERBERATION RESEARCH OVERVIEW

E. MORITZ

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ADMINISTRATIVE INFORMATION

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Prominent computational and theoretical approaches to the modeling of reverberation processes in the sea are reviewed. The work serves as a base line by documenting the work in reverberation since 1970 and the more didactic earlier works. One aim of the review is to identify the essential assumptions of the methodologies currently receiving attention. Additionally, the review identifies some areas that have been under utilized, e.g., zero and level crossing characteristics, and other areas that have benefitted from technological development such as echo-echo correlation and robust detection.

TABLE OF CONTENTS

INTRODUCTION

This memorandum is a review and summary of the prominent computational and theoretical approaches to the modeling of reverberation processes in the sea. This review is neither exhaustive nor does it attend with the same attention to every topic of reverberation attributes and characteristics. It serves as a base line of documenting the work in reverberation since Fortuin's review article[1] and the more didactic works preceding Fortuin's article. Another aim of the review is to identify the essential assumptions of the methodologies currently receiving attention, an example of which is Wilson's work[2] at ARL on validating Middleton's[3] basic theories on covariance and statistical properties of backscattering. The review identifies some areas that have been underutilized, e.g., zero and level crossing characteristics, and other areas that have benefitted from technological development (echo-echo correlation, robust detection). Future work is planned to review in more depth promising areas and to identify and test novel concepts of characterizing stochastic fields in general and reverberation in particular.

The existence of reverberation, in underwater sonar applications, is one of the fundamental limiting factors in recognition (detection and classification) of objects one may wish to be aware of. One may desire information as to range, bearing, and classification of objects or bottom relief. Similar information is of interest in radar applications where the information is carried typically by electromagnetic waves.

Reverberation arises from the interaction of an acoustic or an electromagnetic energy field, modeled by waves, with boundaries and volume scatterers.

The scattering regime is typically divided into the geometric and diffractive domains. The geometric domain is characterized by features much larger than the wavelength of the incident radiation while the diffractive domain's features are of the same order of magnitude of the wavelength.

Analysis in the geometric domain is typically simplified by the use of ray concepts. This is of great use in describing propagation over large distances.

With sound waves interacting with the sea surface, the incident wave length and roughness scale are often of the same order of magnitude and the interaction is characterized by diffraction. This may also be true of bottom surface interactions.

There are two boundary conditions that idealize the extremes. One is the free, elastic, or pressure release boundary. The free boundary is represented by the sea surface. The second is the rigid boundary; e.g., rock bottom.

The wave velocity potential vanishes on a free boundary while the directional derivative of the potential vanishes on the rigid boundary.

The interaction of sound with boundaries depends on:

1. Frequency of incident wave
2. Geometry of source and receiver
3. Transient nature of incident wave
4. Temporal variation of the boundary. The sea surface varies in time, raindrops, leaves change position with wind.
5. Geometry of boundary
6. Material characteistics of boundaries.

Reverberation is often referred to as unwanted returned energy which masks the wanted signal or echo. Urick[4] calls the sum of all the scattering contributions from all the scatterers reverberation.

Reverberation has several features which distinguish it from noise.[5] Paramount among these is the fact that reverberation is generated by the sonar itself. Additionally, the spectral characteristics of reverberation are essentially the same as the transmitted signal, the intensity of reverberation varies with the range of the scatterers, and, finally, the intensity varies with the intensity of the transmitted signal. The last fact is responsible for the lack of improvement in detectability when the source level is increased; i.e., relative to reverberation.

The literature on the subject of scattering and reflection of sound from boundaries is voluminous. It is not the intention of this report to survey the entire field. There are, however, some key references which form the points of departure. Fortuin[1] has surveyed the literature up to the beginning of 1970 on reflection and scattering of sound waves at the sea surface.

MacKenzie,[6] and McKinney and Anderson[7] have considered reflection and backscattering of sound from the ocean bottom. Their work is a cornerstone of all bottom reverberation work to date. A contemporary collection of papers concerning bottom interacting ocean acoustics appears in the collection edited by Kuperman and Jensen.[8]

The major goals of this survey are to identify the methods that are currently used in characterizing reverberation and to distill the essential mathematics used in doing so, as well as identifying several potential new means of characterizing reverberation. In identifying new means of characterizing reverberation, attention is focused on obtaining features which are not used in the mathematical framework in the past, rather than identifying only new algorithms or approaches to make the standard approaches less time consuming or more comprehensive.

The rewards of additional methods or features by which one can characterize reverberation are in the increased ability to recognize signals or target echoes, as well as obtaining a more accurate simulation of reverberation. In the simulation arena, there are two aspects: one in computer simulation for testing equipment performance and the other in countermeasure application; e.g., generate a false reverberation-like field.

Any additional methods of characterizing reverberation can be used as predictors of other reverberation measures as well as in casting light on the mechanisms that generate reverberation. NOTE: The use of the word measure in this report is intended for the mathematical quantification of some attributes; in other words, a metric on a space, dimension of a process such as topological dimension, a statistic, etc.

The prominent descriptive methods in reverberation characterization are given in a group of papers and reports that originated at the University of Texas' Applied Research Labs.[2 9 10 11 12 13 14 15]

A review of reverberation, scattering, and echo structure where reverberation is restricted to receiver being near the transmitter is given by Claude Horton, Sr.[9] Horton deals mostly with different models for the scattering from rough surfaces and points out the assumptions and difficulties of the specific models.

The reverberation studies used for characterizing purposes fall into three categories: (1) computer simulation from which reverberation returns are generated, and then time and ensemble averages are calculated; (2) model tank observations for cast surfaces which may be periodic or randomly rough; and (3) observations of reverberation at sea or at a lake.

An example of computer studies is the simulation of reverberation from a moving sea surface conducted by Bourianoff and Horton.[16] The sea surface is generated by using a 100-term Fourier polynomial with random phases. The polynomial is of the form:

$$F(x,t) = \sum_{m=1}^{100} a_{2m+1} \cos(k_{2m+1}x - \omega_{2m+1}t + \varepsilon_{2m+1})$$

ε_{2m+1} are the random phases distributed uniformly in the interval $(0, 2\pi)$ with new phases generated for each sample. Amplitudes are generated from the power spectrum $S(\omega)$ of the wave spectrum by:

$$a^2_{2m+1} = 2S(\omega_{2m+1})(\omega_{2m+2} - \omega_{2m})$$

for a Neuman-Pierson[17] wave spectrum

$$S(\omega) = \frac{\alpha_o}{\omega_f} \; g^2 e^{-\beta(\omega_o/\omega)^4}$$

$g = 980$ cm/sec^2

$\omega_o = g/u$ 1/sec

u = wind velocity in cm/sec

$\alpha_o = 8.1 \times 10^{-3}$

$\beta = 0.74$.

The results of that simulation, restricted to the Neuman-Pierson wave spectrum and pulses which are short compared with the dominant wave length of the scattering surface, show that means, variances, and covariances are different for time averages as compared to ensemble averages. In the study, it was seen that variances computed as ensemble averages of the second order moment were not constant and hence, the reverberation was not a stationary process. The covariances were computed for the time series as well as the ensembles and significant differences were seen. Specifically, the ensemble average oscillated more rapidly and decayed more rapidly than the time average The frequency of oscillation of the individual covariance functions was higher than the center frequency of the transmitted pulse. The behavior was attributed to the smallness of the insonified area which "produced" a backscattering coefficient which accentuated the higher frequencies. This model did not fit experimental results.

STATISTICAL THEORIES OF REVERBERATION - THE MIDDLETON APPROACH

The task of developing a deterministic theory of reverberation has proven to be formidable. There is the theoretical difficulties of solving quite complex boundary value problems for which analytical tools are only partly developed. There is also the practical difficulties of identifying all the parameters affecting the reverberation process and obtaining sufficiently accurate measurements of these parameters. In order to side step these problems, Middleton and his co-workers[10 11] developed a semi-empirical statistical approach which will be discussed below.

In characterizing data, two papers by Plemons, Shooter, and Middleton[10 11] set the stage for analysis of signals from lake and sea surfaces. These papers will be referred to as PSM.

PSM point out the requirement for adequate statistical description of the reverberation process. There are two observations, really assumptions, which have some experimental support; namely,

1. The reverberation processes are generally Gaussian as a result of large number of scatterers.

2. The covariance function provides sufficient description of the reverberation processes for signal detection and extraction requirements.

The current view of the adequacy of these assumptions will be discussed later; however, these form the starting point for numerical characterization. Another key element discussed by PSM is the need for suitable ensemble averages. Prior investigations typically used time-averages on single-time functions; however, since the dynamics and changing environmental conditions vary, there is little agreement in measurements based on time averages. PSM claim that theirs is the first systematic use of ensemble averages used for detailed analysis of non-stationary mean intensity and covariance of reverberation. The second order statistics are used to study and test Middleton's point scattering models.[3]

The point scattering models of Middleton are also developed by Faure[18] and Ol'shevskii.[19] One may collectively call it the FOM approach. The FOM approach is based on the essential assumption that the reverberation is the result of scattering from point scatterers located independently and randomly in space and re-radiating incident radiation in an independent manner in time. The approach is quasi-phenomenological in that there is no a priori specification of the impulse function of the point scatterers; hence, no a priori calculation of reverberation on an absolute scale can be performed. Experimental data are used to calibrate such models. The improvement is in the elimination of the need for boundary conditions and solutions of reflection/scattering equations with stochastic boundary conditions.

Since the statistics that Middleton's models yield are the variances and co-variances, PSM look for these statistics. Additionally, the data sets are validated. The validation consists of tests for homogeneity and independence. The validation of homogeneity implies the stability of the scattering mechanism; in other words, the density of scatterers is examined; fluctuations in density will lead to data that are inhomogeneous. Tests for homogeneity include the Kolmogorov-Smirnov two sample test and the Wilcoxon rank-sum test. Other tests for homogeneity also exist and will be re-examined in more detail later.

PSM make the assumption that the reradiative properties of each scatterer are time invariant and frequency insensitive; i.e., the scatterers are assumed to have a constant dynamic cross-section $\gamma_o(\lambda_T)$ which depends only on location and direction of incoming illumination. The assumption also includes neglect of Doppler effects due to platform or scatterer motion. The j^{th} scatterer is represented by a stochastic filter with the impulse function

$$h_j(\tau\ \lambda_{T_j}) = \gamma_{oj}(\lambda_{T_j})\ \delta(\tau - \lambda_j)$$

where γ_{oj} is the dynamic cross section for scatterer located at $\lambda_t(\lambda,\phi)_j$.

These assumptions lead to a received signal

$$U_j(t) = \int_{-\infty}^{\infty} h_j(\tau/\lambda_T)\, S(t - \tau)d\tau$$

where S(t) is the signal that illuminates scatterer j [due to the δ-function structure, $U_j(t) = \gamma_{oj} S(t - \lambda_j)$].

The receiver then "sees" the reverberation as a sum of all the basic wave forms expressed as

$$X(t) = \sum_j^M U(t_j, \lambda_j, \theta_j)$$

where the summation is over all contributing scatterers. θ_j is the set of random parameters associated with j.

Now if reverberation has zero mean $\langle X(t)\rangle_{ens.\ av.} = 0$ for all t, then the complex covariance function is defined by

$$K(t_1, t_2) = \langle X(t_1)^* X(t_2)\rangle_{ens.\ av.}$$

PSM make use of narrow band input signals which are represented by the complex form

$$S(\lambda) = S_o(\lambda)\exp(i\omega_o\lambda); \quad S_o(\lambda) = A_o(\lambda)\, e^{i\phi(\lambda)}$$

$S_o(\lambda)$ is the complex enveloped of $S(\lambda)$

$A_o(\lambda)$ is the real envelope

$\phi(\lambda)$ is the real phase.

$A_o(\lambda)$ and $\phi(\lambda)$ vary slowly with respect to $e^{i\omega_o\lambda}$.

The quantity $H_o(\tau)$ is the complex envelope of the covariance function and is defined as

$$H_o(\tau) \equiv \int_{-\infty}^{\infty} S_o(\lambda)^* \, S_o(\lambda + \tau) \, d\lambda \equiv 2K_o(\tau) \exp[i\phi_o(\tau)]$$

$$\left.\begin{array}{l} K_o = 1/2\,|H_o(\tau)| \\ \phi_o = -\tan^{-1}(\mathrm{Im}H_o/\mathrm{Re}H_o) \\ \text{thus} \end{array}\right\} \quad \text{are real quantities}$$

$$K(\tau/t_1) = G(t_1)\, K_o(\tau) \cos[\omega_o\tau + \phi(\tau)]$$

where G is a function which is not determined in PSM but where a normalized covariance function extracts and eliminates the need for this funct .

The normalized covariance function is then

$$\langle K\rangle_N(\tau\,|t_1) = [2\langle K\rangle_o(\tau)/E] \cos(\omega_o\tau + \langle\phi\rangle_o(\tau))$$

E is the energy in the complex transmitted signal $\equiv \int_{-\infty}^{\infty} |S(\lambda)|^2 d\lambda$.

Another requirement is the prevention of intermixing reverberation returns which is achieved by proper spacing of output signals or pings. This requirement carries the label of independence of observations.

The demonstration of homogeneity, i.e., that data come from the same parent population, and independence, i.e., that data contain no contamination of one observation by another, is required.

PSM and other ARL investigators use the quadrature sampling techniques to convert analog signals to digital signals. This technique was developed by Grace & Pitt.[12] The reverberation return is expected to be narrow band since the transmitted signal is narrow band and thus the reverberation return is expressed as:

$$X(t) = X_c(t) \cos \omega_o t + X_s(t) \sin \omega_o t$$

ω_o = transmit center frequency

X_c, X_s = quadrature components which vary slowly compared with $\cos \omega_o t$.

Ensembles at time t_i are constructed by selecting the value of some attribute, e.g., amplitude, at a time t_i from each reverberation event. Different ensembles are formed by choosing different ti.

An ensemble statistic may then be constructed; for instance, the estimate of a mean amplitude at time t_1 would be evaluated

$$\langle X(t_1)\rangle \text{ ens. av.} = \frac{1}{N} \sum_{i=1}^{N} X_i(t_1)$$

where N is the number of reverberation observations or records that are taken.

An experimental covariance function can be evaluated as

$$\langle K\rangle\ (t_1,t_2) = \frac{1}{N} \sum_{i=1}^{N} X_i(t_1)\ X_i(t_2).$$

If one follows PSM's approach for narrow band signals, the covariance function may be expressed as

$$\langle K\rangle\ (t_1,t_2) = \langle K\rangle_o(t_1,t_1 + \tau)\ \cos[\omega_o\tau + \langle\phi\rangle_o\ (t_1,t_1 + \tau)]$$

where

$$\langle K_o\rangle\ (t_1,t_2) = [\langle R\rangle_x^2\ (t_1,t_2) + \langle\Lambda\rangle_x^2\ (t_1,t_2)]^{\frac{1}{2}}$$

where $\langle R\rangle_x$ and $\langle\Lambda\rangle$, the quadrature components of the covariance are:

$$\langle R\rangle_x = \frac{1}{2} \cdot \frac{1}{N} \sum_{i=1}^{N} [X_{c,i}(t_1)\ X_{c,i}(t_2) + X_{s,i}(t_1)\ X_{s,i}(t_2)]$$

$$\langle\Lambda\rangle_x = \frac{1}{2} \cdot \frac{1}{N} \sum_{i=1}^{N} [-X_{c,i}(t_2)\ X_{s,i}(t_1) + X_{c,i}(t_1)\ X_{s,i}(t_2)]$$

leading to the estimate $\langle\phi\rangle_o$ of the phase ϕ_o according to

$$\langle\phi\rangle_o = -\tan^{-1}\{\frac{\langle\Lambda\rangle_x}{\langle R\rangle_x}\}\quad .$$

Local stationarity is tested via the requirement that

$$\langle\phi\rangle_o(t_1,t_1 + \tau) = -\langle\phi\rangle_o(t_1,t_1 - \tau)$$

hold; i.e., compare the phase for positive values of τ with the negative image of the phase when τ is negative.

EFFECT OF ENSEMBLE SIZE ON COVARIANCE

PSM pay attention to the fact that experimentally one deals with a finite number of observations and ensemble averaging is thus performed over a finite number of reverberation returns. The experimental co-variance is therefore only an estimate of the true infinite sized ensemble co-variance. The variance of the co-variance should decrease as $0\ (M^{-1})$ where M is the size of the sample ensemble. PSM argue that a sample size of 150 members is acceptable.

PSM also study the estimate of covariance using time averages where the time average over a single member must be used. For the j^{th} ensemble member, the time averaged co-variance then appears as

$$C_j(\tau|T_1,T_2) = \frac{1}{T}\int_{T_1}^{T_2} X_j(t)\ X_j(t + \tau)\ dt; \quad T = T_2 - T_1$$

in order for $c_j(\tau|T_1,T_2)$ to equal the ensemble covariance the following requirements need to be met: (1) $T \to \infty$, (2) stationarity, and (3) ergodicity.

Other works to originate from ARL concerning the subject of reverberation and in the line of the Plemons, Shooter, and Middleton approach include those of Frazer[13] and Wilson.[2] The objective of Frazer's study is the attainment of a more precise underlying statistical distribution of the scattered fields. Frazer points out that the majority of studies focused on the examination of surface backscattering strength with assumptions that, as a result of large number of scatterers, the outputs of individual receiver elements should be zero mean Gaussian distributed. The conclusions of his studies include the desire for a stronger delineation of the conditions for producing non-Gaussian reverberation and detecting it.

Wilson's study[2] continues along the lines of ARL's earlier work in verifying and calibrating the Middleton model of reverberation. Expanded experimental attention is given to the study of horizontal and vertical co-variance; the first four univariate moments of the reverberation are examined

and normality tests are applied. Additionally, measurement and interpretation of multiple receiver reverberation are investigated. Specific results on the covariance include (1) decrease of a value of 0.1 within a separation of four wave lengths of the normalized envelope of the horizontal covariance; (2) the lower bound of the vertical covariance as a function of spectral separation is 0.2; (3) the first four moments of mean, variance, skewness, and kurtosis contained an oscillatory component which depended on the order of the moment; i.e., the n^{th} moment appeared to oscillate at fundamental frequencies of $n\omega_o$ where ω_o is the transmit frequency; and (4) ensembles were found to be non-normal due to slight skew and large kurtosis. Other details of the structure of the covariance envelopes and phases are presented which reinforce the claim of dependence of amplitude and co-variance structure on the geometries of transmitter/receivers, pulse widths, frequencies, and other parameters.

It is appropriate to note here another fundamental investigation which appeared in report form only; namely, the work of J. Blue.[14] Blue's report in effect set the stage for the other ARL works of the 1970s. It is more operationally oriented since it culminated in the evaluation of the performance of signal processors against the recorded reverberation.

Blue's report is of specific importance since it obtains reverberation *generated* by bottom backscattering. Most of the reverberation work is for surface generated backscattering. The signals used by Blue are 1 msec, 80 kHz, cw pulses, where the projector and receiver arrays are positioned 9 feet off the bottom, for a 3-degree beam width at -3 dB. Blue uses the Edgeworth series to describe departures from Gaussianity of the amplitude distribution, or departures of the envelope distribution, from the Rayleigh distribution. Reasons for such departures are the insufficiency of ensemble sizes and the possibility of a small number of scatterers being involved in scattering at any one time. These conjectures are supported by the observations that the amplitudes departed from the Gaussian distribution and correspondingly the envelopes were not Rayleigh distributed. Blue attributed the non-Gaussian features of the "operational" ensemble data to the inhomogeneous character of the returns. A normalization procedure was applied to the raw or "operational" data. The instantaneous values were normalized over 3 msec locally stationary portions of each return by dividing by the RMS estimates of each return. This procedure led to good fits with the Gaussian distribution.

The comparisons of square law and multiplicative detectors such as inhomogeneous reverberation demonstrated that while the square law detector was superior to the multiplicative detector, the detection loss is lower for the multiplicative detector. Blue also shows that inhomogeneous reverberation degrades the performance levels obtained in homogeneous reverberation.

Another investigation of bottom reverberation is that of Pitt.[15] Pitt's results show that a smooth estimate for the backscattering was difficult to obtain, even with good physical conditions. Pitt stresses that the ensemble statistics obtained were independent of the area sensed for a wide range of areas. The short cw and long linear FM pulses appear to be distributed with

the same Rayleigh-like forms. The descriptive tools were plots of relative level (-dB) versus grazing angles, estimated backscatter coefficient versus grazing angles, envelope statistics of number of occurrences versus amplitude in form of histograms fitted with Rayleigh distribution, and output S/R levels versus input signal/reverberation (S/R).

The paper of Lord and Plemons[20] undertakes the task of characterizing and simulating signals reflected from the sea surface in the forward direction. The sea surface is characterized by a roughness parameter $g = 4\pi\delta \sin\theta/\lambda$; δ = rms surface wave height, λ the acoustic wave length, and θ the grazing angle. The signals are quadrature sampled. A random variable, $\zeta = E/E_{sp}$, is used to characterize returns where E = energy of surface scattered pulse, and E_{sp} is the energy corresponding to scattering or specular reflection from a flat surface. E_{sp} serves as an upper bound or normalization constant.

A unimodal, hypothetical, probability function is used to simulate the distribution according to

$$f(\zeta;\alpha,\beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \zeta^{\alpha-1} (1 - \zeta)^{\beta-1} \text{ for } 0 \leq \zeta \leq 1$$

where $f \equiv 0$ elsewhere. The parameters in this theory are then α and β. The means and variance of ζ can be calculated for the Beta distribution (the function given before) and are:

$$\mu_\zeta = \alpha/(\alpha + \beta)$$

$$\delta_\zeta = \alpha\beta/(\alpha + \beta)^2(\alpha + \beta + 1) \quad .$$

The parameter estimates $\hat{\alpha}$ and $\hat{\beta}$ are then obtainable as:

$$\hat{\alpha} = \hat{\mu}_\zeta \; [(\hat{\mu}_\zeta | \hat{\sigma}^2_\zeta)(1 - \hat{\mu}_\zeta) - 1]$$

$$\hat{\beta} = (1 - \hat{\mu}_\zeta)[(\hat{\mu}_\zeta | \hat{\sigma}^2_\zeta)(1 - \hat{\mu}_\zeta) - 1]$$

where $\hat{\mu}_\zeta$ and $\hat{\sigma}_\zeta$ are the sample estimates.

Lord and Plemons then compare the observed data and postulated Beta distribution via the Kolmogrov-Smirnov test for the cumulative distribution functions

$$\text{cdf of } \hat{f} = F(\zeta;\hat{\alpha},\hat{\beta}) = \int_0^{\zeta} f(x;\hat{\alpha},\hat{\beta})\, dx$$

The empirical cdf is computed from the ordered samples. The K-S test indicated that there was no reason to reject the hypothesis of a Beta distribution at the 5 or 10 percent levels of significance. The prime use of this result is claimed to be in Monte Carlo simulation.

Additional structure in the pulses is investigated via the assumption of autoregressive or recursive features. The assumption is supported by the apparent temporal coherence of the forward scattered pulse.

The linear autoregressive model used is

$$S_r(j,1) = Z(j,1)$$

$$S_r(j,k) = \sum_{\ell=1}^{\ell_k} A(k,\ell)\, S_r(j,k-\ell) + Z(j,k)$$

$S_r(\ ,\ )$ represents surface reflected signals

$Z(\ ,\ )$ represents zero-mean additive random variables

$A(\ ,\ )$ is the set of regression constants.

j ranges over the number of pulses in the ensemble $1 \rightarrow n_p$, n_t is the time increment, and n_p is the number of pulses $(1 \le j \le n_p,\ 2 \le k \le n_t)$. ℓ_k is the order of the autoregressive process.

The least squares estimators are obtained by minimizing the squared error

$$S^2(k) = \sum_{j=1}^{n_p} \left| S_r(j,k) - \sum_{\ell=1}^{\ell_k} A(k,\ell)\, S_r(j,k-\ell) \right|^2$$

where successive sets of equations are formed by setting

$$\frac{\partial S^2(k)}{\partial A(k,n)} = 0 \quad .$$

Lord and Plemons demonstrate with this scheme that the quadrature components at any given time are largely determined by their immediate predecessors and less so on the distance past. Thus, while recognizing that no insight into the scattering mechanism is obtained, it is shown that a first or second order linear autoregressive model provides a reasonable simulation of the non-stationary surface reflected signals.

Other examples of reflection and scattering models and experimental results are available; however, it is not the purpose here to review material that is already reviewed by Fortuin[1] and Horton.[9] It is, however, appropriate to note the existence of the Marsh-Kuo approach given in some papers in the early 60s.[21,22,23,24]

GEOACOUSTIC MODELS AND ECHO CORRELATION TECHNIQUE

The statistical approch of Middleton described in the last section is complemented by the geoacoustic models, and echo-echo correlation techniques possible with aid of contemporary technology. The geoacoustic model used by Russian investigators described here is useful in understanding the methodology required for incorporation of multiple scales of inhomogeneities.

Foreign investigations of sound scattering by the ocean bottom follows the experimental investigations cited before. The review of Bunchuk and Zhitkovskii[25] is representative of available foreign results. The foreign papers do not offer any novel information or methodology; however, it is illuminating to observe the similarities in approaches.

Ivakin and Lysanov[26] investigate bottom reverberation and develop[27] a geoacoustic model of the bottom with a view of verifying the insensitivity of the results of Reference 27 to varying the form of the correlation coefficient of the refractive index fluctuations.

The geoacoustic model assumes a bottom thickness, h. The sediment is regarded as a water saturated medium where the average values of sound velocity and density differ only slightly from one sublayer to another and the upper sedimentary layer differs very slightly from the water-only layer. The result of this model is that there is no reflection from the upper sedimentary interface at all, but rather scattering appears from inhomogeneities in the sediment layer.

The coefficient of backscattering from an absorbing layer with random inhomogeneities is

$$M_s = (2\beta)^{-1} M_v \sin \psi$$

where

β = sound absorption coefficient

M_v = volume scattering coefficient in the non-absorbing medium.

The above expression is valid for $2\beta h/\sin X \gg 1$. If the linear dimensions of the scattering volume are larger than the inhomogeneity scale, the volume scattering can be related to energy spectrum $G(q)$ by

$$M_v = 2\pi k^4 \, G(q)$$

where the energy spectrum is given by

$$G(q) = \frac{1}{(2\pi)^3} \langle \mu^2 \rangle \int_{-\infty}^{\infty} N(r) e^{i\vec{q}\cdot\vec{r}} \, dr$$

where $\langle \mu^2 \rangle$ and $N(r)$ are the mean-square value and correlation coefficients of the refractive index fluctuations; $\vec{q} = \vec{k} - \vec{k}_o$, $\vec{k},\vec{k}_o$ are the incident and scattered wave vectors.

Observations indicate that the absorption coefficient is proportional to frequency; thus, for frequency independent scattering coefficient the energy spectrum must be proportional to k^{-3}. Anisotropic inhomogeneities are of a large scale in the horizontal direction and small in the vertical-depth scale. The correlation coefficient is then decomposed as

$$N(\vec{r}) = N_1(z) \cdot N_2(\rho) \qquad \rho = (x,y)$$

which leads to

$$G(q) = \langle \mu^2 \rangle \, G_1(\gamma) \, G_2(v)$$

where $G_1(\gamma)$ is the normalized energy spectrum of small scale inhomogeneities, $G_2(v)$ of the large scale inhomogeneities.

For example:

$$G_1(\gamma) = \frac{1}{2\pi} \int_{-\infty}^{\infty} N_1(z) \, e^{i\gamma z} \, dz = \frac{1}{2\pi} \int_{-\infty}^{\infty} N_1(z) \, d_z = \frac{z_o}{\pi} = \text{const.}$$

$$G_2(v) = \frac{1}{2\pi} \int_{-\infty}^{\infty} N_2(\rho) \, e^{iv\rho} \, d\rho \quad .$$

$G_1(\gamma)$ is essentially a constant due to small scale assumption leading to $e^{i\gamma z} \cong 1$.

For horizontally isotropic inhomogeneities, the following form is used:

$$N_2(\rho) = \exp(-|\rho|/\rho_o) \qquad \rho = \sqrt{x^2 + y^2}$$

which yields

$$G_2(v) = \frac{\rho_o{}^2}{2\pi}\,(1 + v^2\rho_o^2)^{-3/2}$$

and for $v\rho_o >>1$, $G_2(v) = (2\pi\rho_o v^3)^{-1}$.

The backscattering case $v = 2k\cos\psi$ leads to

$$G_2(v) = 1/(16\pi\rho_o k^3 \cos^3\psi)$$

and

$$M_s = \langle\mu^2\rangle(k/\beta)(z/\rho_o)\sin\psi/16\pi\cos^3\psi.$$

One is now interested in varying the form of the correlation coefficient. Operationally, this is justified since different bottoms will be described by different conditions. Ivakin and Lysanov recommend the use of a certain class of functions wherein a change of form of the correlation coefficient does not alter the fundamental results. The class of function investigated is that where $N_2(\rho)$ has a non-vanishing first derivative for $\rho = 0$. This class can be shown to maintain an energy spectrum $G_2(v) \sim v^{-3}, v\rho_o >>1$. Since in reality there are no infinite gradients, in addition to the inhomogeneity scale ρ_o, an additional parameter ρ_1 characterizes the minimum thickness of the transition layers between individual inhomogeneities and has dimensions of length.

$\sqrt{\langle\mu\rangle^2/\rho_1}$ determines the limiting gradient of the random field μ in the medium.

The function

$$N_2(\rho) = (e^{-|\rho|/\rho_o} - \varepsilon e^{-|\rho|/\rho_1})(1 - \varepsilon)^{-1}, \ \varepsilon \equiv \rho_1/\rho_o$$

will have a zero derivative for $\rho = 0$ and differ from single-scale correlation only in the vicinity of zero.

The energy spectrum that corresponds to the above function is

$$G_2(v) = \frac{\rho_o^2}{2\pi(1 - \varepsilon)} \left[\frac{1}{(1 + v^2\rho_o{}^2)^{3/2}} - \frac{\varepsilon^2}{(1 + v^2\rho_1^2)^{3/2}}\right] .$$

In the interval $1/\rho_o \leq v \leq 1/\rho_1$, then it can be shown that the models yield invariant characterization of the backscattering. These results are further extended to multiple scale models.

A somewhat different approach altogether is taken by Dunsiger, Cochrane, and Vetter.[28] Dunsiger et al were interested in characterizing the seabed using ping-to-ping echo coherence. The model they used is a two process model where a deterministic but unknown reflection filter operates in parallel with a random scattering filter. They remove large scale topography effects by realigning the echoes to a standard time reference. Then coherence versus frequency is studied using a broad spectrum impulsive excitation which, after processing, yields data in bandwidth from less than 1 kHz to more than 10 kHz. The coherence or correlation approach yields reasonable results for soft bottoms while harder bottoms yield relations which are inconsistent with any master curves derivable from a linear, parabolic, or Gaussian correlation function.

Other studies of the dependence of spatial and temporal correlations of scattered underwater sound are those of Clay and Medwin[29 30] who study the correlation for forward scattering when source and receiver are far away and surface slopes are assumed to be small such that no shadowing effects occur. The experimental part was conducted in a test tank at the Naval Postgraduate School.

It is thus quite apparent that a substantial amount of theoretical development and experiments designed to verify them are based on correlation investigations where coherences or covariances are measured either for amplitudes alone or amplitudes and phases. General studies on covariances coherences and spectral analysis from the pure mathematical point of view are given by Middleton[31] and Nuttal.[32] Middleton's book[31] contains a thorough discussion of many aspects of statistics, probability, and coherence/covariance analyses as they apply to communications systems. These methods form the basis of the work of ARL described earlier.

In this context, it is appropriate to note the report of Green[33] who investigated the target signature of a mine for large bandwidth-time (BT) product with greater than CW pulses. The replica correlator is accepted as the optimum filter for an echo embedded in Gaussian white noise and when the echo exactly replicates the transmitted pulse. The Echo-Echo Correlation technique, as the name implies, attempts to correlate one echo with another and is particularly adapted to account for experimental and target induced variabilities.

Green emphasizes that there is a great deal of variability in both the echo shape and echo power. The attempt to obtain more target structure by using higher resolution pulses did not succeed as projected. It was observed that for a given pulse bandwidth, Echo-Echo Correlation requires three times the same BT product; also, EEC does not provide precise range information available with RC. However, EEC is claimed to be advantageous over RC for the following capabilities: (1) simple processing using time domain correlation in real time, (2) reduced display requirements, (3) stable correlation performance with increased bandwidth (RC does not), (4) improved false alarm rate, (5) better motion tolerance, and (6) better suited for use with Pseudo Random Noise (PRN) signals.

LEVEL CROSSINGS ANALYSIS

A completely different approach to study of reverberation is possible with the use of zero-crossing and level-crossing analysis techniques. The most important feature of level-crossing analysis is that it is implicitly focused on features relating to phase rather than amplitude. The zero crossing approach is that where the rate of occurrence of zero-level amplitude for noise and signal ⊕ noise are compared. Rice[34] investigated the distribution of crossings of the y = 0 axis of a stationary Gaussian noise function y(t) and derived the following formula for the average number of zero crossings per unit time

$$A = 2\left[\int_0^\infty f^2 \omega(f)\, df \Big/ \int_0^\infty \omega(f)\, df \right]^{\frac{1}{2}}$$

where $\omega(f)$ is the spectral density of the function y(t). Bom and Conoly[35] extended this work to develop the zero-crossing shift as a detection method. Their work had been commented upon by Riter and Boatright[36] and replied to by Bom and Conoly.[37] They recognize the importance of investigating the distribution of time intervals τ between consecutive zero level crossings and point out Rice's observation of the substantial difficulty involved. Bom and Conoly claim that at the time of their work no one had found a satisfactory theoretical solution, and hence they made use of an empirical approach for finding the probability density function $p(\tau)$ that would approximate the experimentally observed distribution.

The procedure used by Bom and Conoly determined the zero crossing by passing a noise signal and counting the number of occurrences within a selected range $\tau + \Delta\tau$ over a fixed time. The probability density of Pearson type III family was used for convenience:

$$p(\tau) = [\rho/\Gamma(m)]\ (\rho\tau)^{m-1} e^{-\rho\tau}$$

with $\rho > 0$ and $m > 0$ constant.

This type of distribution coupled with an assumption of very rapid decorrelation between successive intervals makes the zero crossing a renewal process.

For $m = 1$, $p(\tau) = \rho e^{-\rho\tau}$ and the probability that n more crossings occur before $t = T$ is

$$U_n(T) = [(\rho T)^n/n!]e^{-\rho T}$$

as $\rho T \to \infty$, the estimates of crossing rate n/T are asymptotically normally distributed about ρ with variance ρ/T. In the general case $p = p(\rho,m)$ above, we have an asymptotically normal distribution about ρ/m with variance ρ/m^2T. A series of 1-second counts is then made $\zeta_1, \zeta_2, \zeta_3 \ldots \zeta_k$ and the mean rate evaluated as

$$Z = \frac{1}{k} \sum_{i=1}^{k} \zeta_i \quad .$$

For a large enough T, the estimate Z forms a normal distribution about a mean value $A = \rho/m$ and then Z can be considered as independently drawn from a distribution $N(A,\sigma)$. When the spectral content changes slowly so that the distribution can be assumed stationary over the sampling interval, it is found that the mean changes faster than the variance of the distribution; and the resulting distribution can be regarded as the initial distribution $N(A_o,\sigma)$ with a shifted mean; i.e., $N(A_1,\sigma)$ and a Neyman-Pierson detection scheme can be used.

Riter and Boatright comments generalize to discussion of level-crossing detectors. The detectors count the rate at which a signal crosses a given threshold in the positive direction or up-going direction. They refer to Papoulis[38] who shows that the level crossing rate $A_a(\tau)$ is

$$A_a(\tau) = \tfrac{1}{2} A_o(\tau)\ e^{-a^2/2R(o)}$$

where $A_o(\tau)$ is the number of zero crossings in time τ and R(o) the autocorrelation of the signal ● noise at t = 0.

The concept of level crossing also appears in an informal report authored by McLeroy, Leadbetter, and Wegman.[39] The study uses two statistical techniques; namely, comparisons of zeores of reflected waveforms and spectral comparisons of the transmitted and reflected waveforms. The targets used were

a small sphere and a larger sheet metal object formed of short concentric cylinders stationed on a single axis. The zero pattern crossings were summarized by means of histograms of length intervals between successive zeroes. The zero-crossing methods involved the concepts of instantaneous wave and frequency. An arbitrary waveform $x(t)$ is represented by the real part in-phase component of the waveform $x(t) + i\hat{x}(t)$ where $\hat{x}(t)$ is the quadrature component of $x(t)$ (Hilbert transform). One can use the representation in terms of a principal value integral

$$\hat{x}(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(s)}{s - t}\, ds \quad .$$

The instantaneous phase ψ is then the argument of $[x(t) + i\,\hat{x}(t)]$ and the instantaneous frequency is $d/dt\ \psi(t)$.

Typical examples are if $x(t) = \cos \omega t$, then $\hat{x}\ (t) = \sin \omega t$ (the quadrature component.

Instantaneous phase = avg $(\cos \omega t + i \sin \omega t)$ = avg $(e^{i\omega t}) = \omega t$.

Instantaneous frequency = $d/dt\ (\omega t) = \omega$.

One may represent

$$x(t) = \int_{-\infty}^{\infty} x^{+}(\lambda)\ e^{i\lambda t} d\lambda$$

then

$$\hat{x}(t) = i \int_{-\infty}^{0} x^{+}(\lambda)\ e^{i\lambda t} d\lambda - i \int_{0}^{\infty} x^{+}(\lambda)\ e^{i\lambda t} d\lambda$$

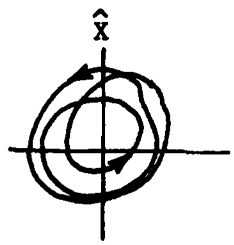
thus

$$x(t) + i\,\hat{x}(t) = 2 \int_{0}^{\infty} x^{+}(\lambda)\ e^{i\lambda t} d\lambda$$

and

$$\psi(t) = \text{Avg}\ \{2 \int_{0}^{\infty} x^{+}(\lambda)\ e^{i\lambda t} d\lambda\} \quad .$$

We may then write $x(t) + i\,\hat{x}(t) = A(t)\,e^{i\psi(t)}$. If we take $x(o) = o$, one could observe that $\psi(t) = 2\pi N(t)$ with $N(t)$ being the number of revolutions of the origin by the complex waveform $x + i\,\hat{x}$ in (o,t). If the vector $(x,\hat{x})$ does not backtrack, then $N(t)$ would be the number of zero crossings. Refer to the phase-space diagram here.



Other references to the zero crossing concepts include the phase filter zero crossing counter of Huggins and Middleton[40 41] and analysis of a narrow band-pass filter of Bendat.[42]

Bendat[42] calculates the average number of zero crossings per second, at the output of a narrow bandpass filter of rectangular shape, when there is a sine wave in Gaussian noise, to be

$$\bar{n}_o = 2f_o\{[S/N + 1 + (f_B^2/12f_o^2)]/[S/N + 1]\}^{\frac{1}{2}}$$

where S/N is the signal-to-noise power ratio

f_B the filter bandwidth

f_o center frequency of the filter.

There are other zero-crossing information displays. The periodmeter[43] measures the period of each cycle, i.e., the distance between every other zero crossing, and is displayed as a height off an arbitrary base line. When noise alone is present, a random distance distribution from base line is present while for a signal the distance between zero crossing is more uniform and the scatter of points is reduced.

In discussing the nature and characterization of reverberation, it becomes apparent that the characterization is dependent upon the detection concepts or at least that the detector used for detecting signals is crucial in determining what features of reverberation should be studied. One important concept in detection is that of Robust Detection, which is used by Dwyer,[44] Poor et al,[45] and Martin and Schwartz.[46]

The robust detector performs well over a range of noise or reverberation distributions. Typically, a robust detector will outperform a detector which uses an optimum Gaussian procedure when the underlying distribution of noise

or reverberation is non-normal. When the underlying distributions are normal, a robust detection procedure performs almost as well as an optimum Gaussian procedure. Robustness is typically evaluated by considering the asymptotic relative efficiency (ARE) versus ε where ε is a perturbation parameter in the cumulative distribution function of the noise of reverberation process. The salient feature of the ARE is that it is a measure of the local asymptotic performance.[46]

Earlier in this review, points that merit detailed discussion were identified. These are (1) adequacy of the assumption of Plemons, Shooter, and Middlteon[3] [11] concerning the Gaussianity assumption and the sufficiency of the covariance function and (2) other statistical tests for features such as homogeneity of data. These topics will be explored in greater detail in future reports dealing with new models and new reverberation characterization techniques. Special attention will also be given to the topic of zero crossings and level crossings making substantial use of the work of Cramer and Leadbetter[47] and subsequent work by Leadbetter.

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